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Effects of ankle and hip muscle fatigue on postural sway and attentional demands during unipedal stance

Etienne J. Bisson [a,*], Daniel McEwen [a,1], Yves Lajoie [b,2], Martin Bilodeau [c,3]

[a] Élisabeth Bruyère Research Institute, Bruyère Continuing Care, School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, 43 Bruyère Street, Ottawa, Ontario, Canada K1N 5C8
[b] School of Human Kinetics, Faculty of Health Sciences, University of Ottawa, 125 University Ave., Ottawa, Ontario, Canada K1N 6N5
[c] Élisabeth Bruyère Research Institute, Bruyère Continuing Care, School of Rehabilitation Sciences, Faculty of Health Sciences, University of Ottawa, 43 Bruyère Street, Ottawa, Ontario, Canada K1N 5C8

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ABSTRACT

The effect of muscle fatigue on quiet standing is equivocal, including its duration/recovery and whether it leads to an increase in attentional demands. The purpose of this study was to assess the effects of ankle and hip muscle fatigue on postural sway and simple reaction time during a unipedal task. Two groups of 14 young adults (mean age = 22.50 ± 3.23) had to stand on their dominant leg for 30-s trials before and after fatigue of hip or ankle flexors and extensors. Half of the unipedal trials were performed in a dual-task condition where subjects, in addition to standing, had to respond verbally to an auditory stimulus. Sway area, and sway variability and velocity in the AP and ML planes were calculated using center of pressure data obtained from a force platform. Voice reaction time was recorded seated and during the dual-task condition to assess attentional demands. A main effect of fatigue was found for AP sway variability ($p = 0.027$), AP sway velocity ($p = 0.017$) and ML sway velocity ($p = 0.004$). Both groups showed increased sway velocity in both directions and in reaction time during the dual-task condition ($p < 0.001$), but reaction time did not increase with fatigue. A group by fatigue interaction was found significant for ML sway velocity ($p = 0.043$). Results suggest that hip and ankle fatigue affected postural control in the fatigued plane (AP) but only hip fatigue affected postural control in the non-fatigued plane (ML sway velocity). However, fatigue did not lead to an increase in attentional demands and increased AP and ML sway velocity had recovered within 30 min.

1. Introduction

The ability to maintain a stable, upright stance is an essential component of daily activities. In order to maintain an upright stance, the CNS must integrate and (re-)weigh information from different sensory systems (vision, vestibular and somatosensation) and modulate commands to the neuromuscular systems continuously. Even though this is an automated process, numerous studies using the dual-task paradigm have shown that tasks like standing or walking require some attentional resources [1]. An increase in attentional demands can be inferred from a reduction in the performance of a secondary task (usually a cognitive task) while the performance on the primary (postural) task remains the same. It is well known that the attentional demands for postural sway regulation increase with the difficulty of the task [2–4], aging [5–7] and pathology [8,9], particularly when proprioceptive information is reduced due to environmental constraints [3–6]. This is not surprising since ankle proprioception is one of the primary regulatory mechanisms for stabilization of the body [10,11].

Muscle fatigue, defined as an acute impairment in the ability to produce maximum force, regardless of whether or not the task itself can still be performed successfully [12], has been shown to impair the mechanical properties of the muscle [13] and the proprioceptive system [14,15] required for postural stability. The proprioceptive impairment due to muscle fatigue could be caused by changes in the discharge patterns of muscle afferents due to metabolite build up leading to potential altered muscle spindles information [15], altered central processing of proprioception via group III and IV afferents [14] and effects on the efferent pathways [16]. However, the relative contribution of fatigue-related changes in mechanical properties and proprioception for postural stability remains to be clarified. Studies on the effect of muscle fatigue and postural stability have repeatedly suggested that proprioception could be the primary mechanism explaining changes in postural

* Corresponding author. Tel.: +1 613 562 6262x1376.
E-mail addresses: ebisson@uottawa.ca, ebisson@bruyere.org (E.J. Bisson), dmcewen@bruyere.org (D. McEwen), ylajoie@uottawa.ca (Y Lajoie), mabilode@bruyere.org (M. Bilodeau).
[1] Tel.: +1 613 562 6262x1654.
[2] Tel.: +1 613 562 5800x4273.
[3] Tel.: +1 613 562 6262x1358.

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sway observed after fatigue [17–23]. The work of Vuillerme et al. [21–23] supports this by showing that the increase in postural sway due to muscle fatigue is not accentuated with vibration [21], is eliminated with light touch [22], and is attenuated with augmented visual feedback [23]. If muscle fatigue induces deficiencies in proprioception resulting in reduced stability of the body, the attentional resources needed to perform the task are likely to increase. However, only one study at present has shown an increase in attentional demands after fatiguing a targeted muscle group (localized fatigue of the plantar flexors) [20]. Since several studies have shown an increase in postural sway after fatiguing various muscle groups [18,24,25], it is reasonable to expect an increase in attentional demands when fatiguing such muscle groups. Although the effect of exercise on cognitive performance is complex [26], and because fatigue of certain muscle groups may have a more pronounced effect on postural control (e.g., hip or knee versus ankle [18]), it could be hypothesized that an increase in attentional demands with fatigue may be specific to the muscle group fatigued.

The purpose of this study was thus to compare the extent to which fatigue of ankle extensor (plantarflexor) and flexor (dorsiflexor) muscles versus fatigue of hip extensor and flexor muscles: (a) increases postural sway in unipedal stance and (b) leads to an increase in attentional demands during a dual-task paradigm. Based on previous results [18,25], it was hypothesized that fatigue of hip muscles would have a greater effect on posture control compared with fatigue of ankle muscles, and this would be associated with a greater increase in attentional demands with fatigue of the hip compared with ankle muscles.

2. Methodology

2.1. Subjects

Two groups, each comprised of 14 young adults between 19 and 30 years of age with no known orthopaedic, cardiovascular or neurological conditions were recruited for this study through convenience sampling. The cognitive status of subjects was assessed using the Mini Mental State Exam [27]. The study was approved by the University of Ottawa and the Bruyère Continuing Care research ethics boards and written informed consent was obtained from each subject prior to their participation in the study.

2.2. Procedures

Subjects were asked to maintain a unipedal stance on their dominant leg, as steadily as possible, while standing on a force platform without their shoes. The leg which the subject would use to kick a ball was considered the dominant leg. Subjects were asked to fixate a black cross placed on the wall at eye level, 2.5 m in front of them. Their arms had to hang by their sides and support from the elevated leg was not permitted. Each subject completed eight 30-s trials for each of the following time points: pre-fatigue, post-fatigue and after 30 min of recovery. For each time point, trials were alternated between a single-task condition (quiet standing alone) and a dual-task condition (quiet standing with the addition of a simple reaction time task). The order of trials was counterbalance between subjects. Simple reaction time (SRT) consisted of responding verbally with the word "top" after hearing an auditory stimulus (1000 Hz, 100 ms) which was randomly dispersed four times throughout the 30-s trial. Subjects were asked to respond to each auditory stimulus as quickly as possible while maintaining their focus on the primary (postural) task (i.e., to be as steady as possible). Prior to pre-fatigue trials, each subject was familiarized with the tasks and three trials of seated SRT were recorded.

2.3. Fatigue protocol

For each group respectively, the ankle or hip flexor and extensor muscle groups were fatigued using a BIODEX system III (Shirley, NY). Starting position for the ankle fatigue protocol was seated with the hip, knee and ankle joints at 90°, 35° and 80°, respectively; whereas the hip fatigue protocol was performed in a supine position with the hip, knee and ankle joints at 180°, 35° and 90°, respectively. For both protocols, knee angle was kept constant and total range of motion was set at 35° for the ankle and 40° for the hip. The non-dominant leg was left hanging free without support to limit its use during the fatigue protocol. The arms were crossed in front of the subject with the waist, knee and ankle securely strapped to eliminate potential compensations. Prior to the fatigue protocol, the peak torque output was measured during three maximal voluntary concentric contractions (MVCs) at $30^\circ\,s^{-1}$ for the extension direction and $120^\circ\,s^{-1}$ for flexion. The fatigue protocol consisted of alternating maximal isokinetic contractions in extension and flexion (same speeds as for the MVCs) for as many repetitions as possible, i.e., until the torque for three consecutive sets of contractions decreased below 50% MVC for both muscle groups. The chosen contraction speeds ($30^\circ\,s^{-1}$ and $120^\circ\,s^{-1}$) were selected based on preliminary testing of the fatigue protocol, to allow reaching the criteria to end the fatigue protocol (50% MVC) relatively simultaneously with both muscle groups. To avoid the effect of an initial recovery during the post-fatigue trials, the fatigue protocol was repeated (re-fatigue) once after the first two trials of each task (single-task and dual-task) were completed. The time elapsed between the end of the fatigue protocol and the start of the postural data collection was 40 s on average.

2.4. Data analysis

Postural data was collected using an AMTI Acu-Gait force platform (Watertown, MA). Three center of pressure (COP) variables were calculated using BioAnalysis 2.1 software (Watertown, MA): sway area, represented by the area of the 95% confidence ellipse (EA in cm^2; which is an ellipse that encloses 95% of the center of pressure data for a given trial (AMTI, Watertown, MA)); sway variability, represented by the standard deviation of the COP around the mean position (SD in cm); and sway velocity, represented by the total COP displacement divided by time (cm/s). The last two variables were obtained for both antero-posterior (AP) and medio-lateral (ML) directions. SRT data was collected with an MP3 recorder fixated to the subject's arm to gather both the start of the auditory stimulus and the verbal response from the subject. The mean of all trials in each condition were calculated and used for statistical analyses. Only 1% of the trials were not used for analyses because of steps taken by the subjects.

Three-way analyses of variance (ANOVAs) were used to assess the effects of group (ankle or hip; independent factor), fatigue (PRE, POST, REC; repeated measures) and tasks (single-task or dual-task; repeated measures) for each of the dependent postural variables (EA, AP and ML SD, AP and ML velocity). A two-way ANOVA was used to assess the effects of group (ankle or hip; independent factor) and condition (seated, PRE, POST, REC; repeated measures) on SRT. All statistical analyses were completed using PASW statistics 18 (IBM, Chicago, IL) with a p-value of 0.05. Post hoc analyses were used when appropriate using a Bonferoni adjustment.

3. Results

Table 1 depicts the characteristics of each group. Independent t-tests showed no differences between groups ($p > 0.05$), except for the time to re-fatigue which was longer for the hip fatigue group ($p = 0.03$). Results for all the postural variables are provided in Table 2.

3.1. Postural sway area

EA results revealed no significant main effect of fatigue ($F = 1.930$, $p = 0.155$), task ($F = 0.002$, $p = 0.968$) or group ($F = 0.151$, $p = 0.701$). All interaction effects were also not significant ($p > 0.05$).

3.2. Postural sway variability

SD AP results showed a significant main effect of fatigue ($F = 3.856$, $p = 0.027$). The main effects of task ($F = 0.457$, $p = 0.505$) and group ($F = 0.052$, $p = 0.822$) and all interaction effects ($p > 0.05$) were found not significant. SD AP increased after fatigue, however, pairwise comparisons showed that a significant

Table 1
Group characteristics.

	Mean (SD)[a]	
	Ankle ($n = 14$)	Hip ($n = 14$)
Gender, # female (%)	10 (67)	9 (60)
Age, years	22.4 (3.0)	23.7 (3.1)
Height, cm	168 (7.6)	169 (10.0)
Weight, kg	66.1 (12.7)	67.0 (10.1)
MMSE score, /30	29.6 (0.6)	29.7 (0.5)
Time to fatigue, s	123 (159.1)	159 (133.4)
Time to re-fatigue[b], s	67.9 (37.8)	127 (85.0)

[a] Unless otherwise stated.
[b] Time of the second fatigue protocol (re-fatigue). t-Tests < 0.05.

Table 2
Mean and standard deviation (SD) of each postural variable during the single (ST) and dual task (DT).

Variables	Task	Ankle group			Hip group		
		pre	post	rec	pre	post	rec
95% ellipse area	ST	8.21 (2.18)	8.73 (2.20)	8.33 (2.83)	7.55 (2.37)	7.98 (1.640)	8.94 (3.12)
	DT	8.04 (1.93)	8.96 (2.70)	8.39 (2.19)	8.00 (2.56)	8.21 (2.04)	8.18 (2.43)
SD AP[a]	ST	0.75 (0.15)	0.82 (0.14)	0.79 (0.17)	0.75 (0.17)	0.80 (0.10)	0.87 (0.18)
	DT	0.75 (0.13)	0.82 (0.15)	0.79 (0.11)	0.78 (0.18)	0.77 (0.15)	0.80 (0.14)
SD ML	ST	0.58 (0.07)	0.57 (0.07)	0.56 (0.07)	0.54 (0.06)	0.53 (0.07)	0.54 (0.09)
	DT	0.58 (0.07)	0.58 (0.09)	0.57 (0.08)	0.56 (0.08)	0.57 (0.08)	0.55 (0.09)
Velocity AP[a,b]	ST	2.53 (0.63)	2.53 (0.56)	2.47 (0.64)	2.24 (0.54)	2.53 (0.70)	2.35 (0.65)
	DT	2.65 (0.75)	2.68 (0.73)	2.57 (0.69)	2.38 (0.54)	2.70 (0.79)	2.42 (0.59)
Velocity ML[a,b,c]	ST	2.71 (0.48)	2.76 (0.52)	2.59 (0.59)	2.43 (0.43)	2.70 (0.54)	2.46 (0.50)
	DT	2.90 (0.61)	2.85 (0.53)	2.82 (0.63)	2.58 (0.48)	2.88 (0.64)	2.56 (0.44)

[a] Main effect of fatigue ($p < 0.05$).
[b] Main effect of task ($p < 0.05$).
[c] Group × time interaction ($p < 0.05$).

difference was found only between pre-fatigue and recovery (mean difference = 0.56, $p = 0.011$). SD ML results revealed no significant main effect of fatigue ($F = 0.902$, $p = 0.412$), task ($F = 4.112$, $p = 0.053$) or group ($F = 0.962$, $p = 0.336$). All interaction effects were also not significant ($p > 0.05$).

3.3. Postural sway velocity

AP sway velocity results revealed a significant main effect of fatigue ($F = 4.666$, $p = 0.017$) and task ($F = 27.697$, $p = 0.000$). The main effect of group ($F = 0.322$, $p = 0.575$) and all interaction effects were found not significant ($p > 0.05$). ML sway velocity results revealed a significant main effect of fatigue ($F = 6.057$, $p = 0.004$) and task (ML; $F = 23.399$, $p = 0.000$). The main effect of group was found not significant ($F = 0.826$, $p = 0.372$). Interaction effects were found not significant ($p > 0.05$), except for the fatigue by group interaction effect ($F = 3.340$, $p = 0.043$). Pairwise comparisons did not show any significant differences between groups in ML velocity for a particular time point (pre, post, rec). However, pairwise comparison showed a significant increase in ML sway velocity after fatigue (post-fatigue) for the hip group (mean difference = 0.283, $p = 0.011$) but not for the ankle group (mean difference = 0.003, $p = 1.000$). Furthermore, the mean difference in ML sway velocity between pre-fatigue and 30 min recovery was non-significant (mean difference = 0.005, $p = 1.000$). Fig. 1 shows the percent change in sway velocity for the ankle group (Fig. 1A and B) and for the hip group (Fig. 1C and D).

3.4. Simple reaction time

SRT results are shown in Fig. 2. Results of the ANOVA showed a significant main effect of condition ($F = 17.275$, $p = 0.000$), but no main effect of group ($F = 0.0213$, $p = 0.648$). The condition by group interaction effect was also found not significant ($F = 0.079$, $p = 0.975$). Pairwise comparisons showed only a significant difference between seated SRT and all standing SRTs for both the ankle and hip fatigue groups ($p < 0.05$).

4. Discussion

Our main results showed that ankle and hip fatigue increased sway variability and sway velocity in young healthy adults during a unipedal stance in the fatigued plane (AP), whereas sway velocity in the non-fatigued plane (ML) increased only after hip fatigue, suggesting a greater decline in postural control with fatigue for this muscle group. When a secondary task was performed simultaneously with the postural task, AP and ML sway velocity increased significantly. However, this effect was the same after fatigue (ankle or hip), and fatigue did not affect SRT, suggesting that the present fatigue protocols did not increase the attentional demands associated with a unipedal stance.

4.1. Effect of fatigue

Our study and several others [18,24,25] show that fatiguing proximal muscles (hip and/or knee) has a greater effect on postural control than distal (ankle) muscles, confirming our first hypothesis. Our results on a unipedal stance task with the eyes open showed that proximal and distal muscle fatigue increased sway velocity in the fatigued plane (AP), but only proximal muscle fatigue increased sway velocity in the non-fatigued plane (ML), as previously documented [18]. When looking at percent change (Fig. 1), fatigue

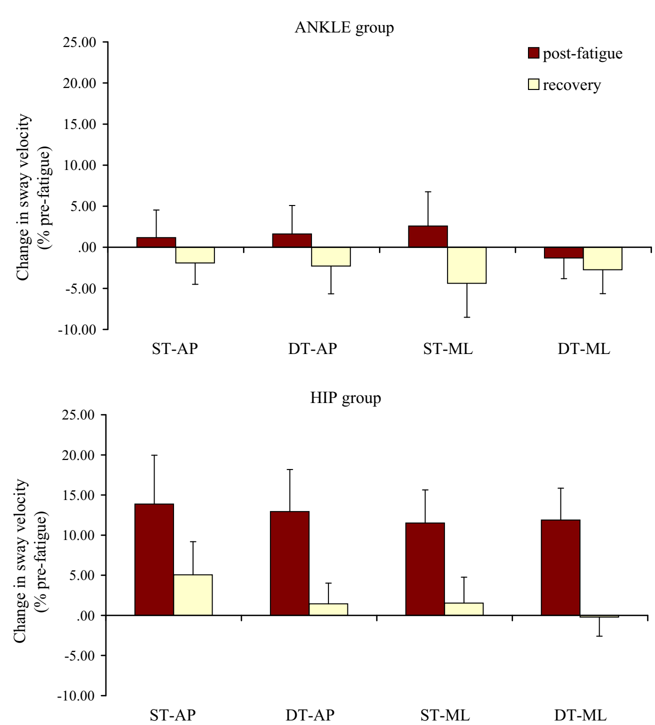

Fig. 1. Percent change in sway velocity (mean and standard error) in AP and ML directions for the ankle fatigue group (top panel) and for the hip fatigue group (bottom panel). ML sway velocity increased significantly immediately after fatiguing the hip muscles only ($p = 0.011$). ST = single-task, DT = dual-task.

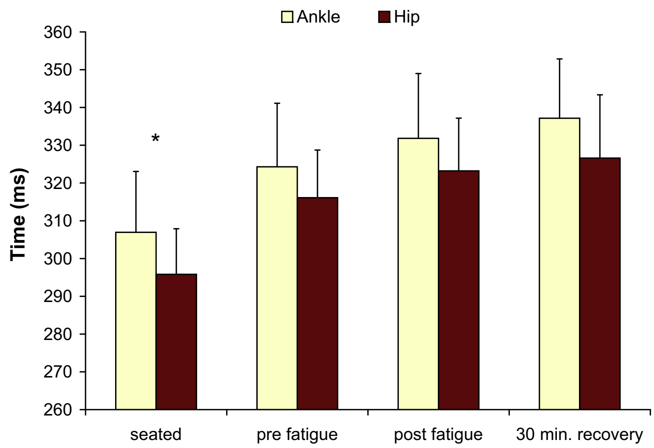

Fig. 2. Simple reaction time (mean and standard error) at each time points for the ankle fatigue group (light bars) and for the hip fatigue group (dark bars). Simple reaction time was significantly different between seated and standing before fatigue (pre-fatigue), standing immediately after fatigue (post-fatigue) and standing 30 min after fatigue (30 min recovery) for both groups (* $p \leq 0.05$).

of the hip flexors/extensors increased ML sway velocity by 13% and AP sway velocity by 12%, whereas fatigue of the ankle plantar/dorsiflexors barely increased sway velocity in either direction (2%). A common explanation in the literature for this joint-specific fatigue effect resides in the compensatory mechanisms available after fatigue [18,24,25]. The ankle strategy is predominantly used during quiet standing but the use of the hip strategy increases with the difficulty of the task [28]. Thus, the unipedal stance is controlled by a combination of ankle and hip strategy [29]. Others [18,24] have suggested that when the ankle is fatigued, the decrease in ankle control (due to impaired ankle proprioception [14,15]) can be compensated by an increase reliance on the hip strategy. In fact, the reliance on more proximal muscles to maintain upright stance has been shown to increase (increased corrective actions at the knee and hip) when proprioceptive information at the ankle is reduced (foam surface and multiaxial platform) [29]. However, impaired proprioception following fatigue of hip muscles may have compelled subjects to rely primarily on an ankle strategy, leading to an increase sway velocity to maintain stability.

Vuillerme et al. [19] have demonstrated that vision alone could attenuate the postural deficits associated with fatigue of the ankle plantarflexors. It should also be noted that with the absence of vision, both ankle and hip fatigue have been shown to increase postural sway [25]. In the present study, subjects were tested with eyes opened, thus reliance on visual information was possible. Consequently, the decrease in ankle proprioception may not have been sufficient to affect sway velocity when vision was available. However, the presence of visual information was not sufficient to compensate for the effect of fatigue induced at the hip on the control of a unipedal stance.

Nonetheless, the effect of fatigue was short-lived since sway velocity decreased to pre-fatigue values after 30 min of recovery. Others [30] have also found a rapid recovery of postural control variables following fatigue. Interestingly, AP sway variability was significantly increased after 30 min of recovery. However, this increase in AP sway variability was minimal and did not lead to a greater sway area (which combines information from both the AP and ML planes).

4.2. Dual-task

In this study, subjects were asked to focus on standing as still as possible during all conditions (primary task). According to such dual-task instructions, it was expected that no differences would be observed in sway area and sway variability between the single-task and dual-tasks, which was confirmed. In contrast, a significant increase in AP and ML sway velocity during the dual-task condition was noted. When the difficulty of a task increases, more activity of the supporting musculature may be needed to remain in a stable posture. Because subjects did not sway more (EA, AP and ML SD did not change), the increase in sway velocity during the dual-task condition suggests an increase in corrective actions [18,31]. Although the articulation of words may cause an increase in sway [32], the time to articulate the SRT used in our study rounds up to only a fraction of the 30-s trial over which each sway parameter was computed. Thus, it is more likely that the increase in sway velocity was due to an increase in attentional demands when subjects were required to respond to the auditory stimulus. In a recent review, Fraizer and Mitra [1] explained that attentional demands were shown to increase during a dual-task, resulting in compensatory activity (increase sway velocity) for the primary task and a decrease in performance of the secondary task. In the present study, this decreased performance was reflected in the increased SRT from sitting when compared to standing.

Contrary to our initial hypothesis, performing a unipedal stance did not require more attention following muscle fatigue, as reflected by the absence of a change in SRT, regardless of the muscle groups fatigued. Also, the increase in sway velocity during the dual-task compared with the single-task was not greater after fatigue. Although this is the first study investigating the attentional cost of fatigue at the hip joint, our results are in contrast with two other studies investigating the attentional cost of muscle fatigue [20,33]. Vuillerme et al. [20] found an increase in SRT during quiet standing with feet together and eyes closed after fatiguing the plantarflexor muscles. Simoneau et al. [33] also demonstrated an increase in SRT during a dynamical task (target tracking) after bouts of treadmill walking. Considering that the postural task used in this study was relatively difficult, we expected an increase in attentional demands due to fatigue. There are two possible explanations for the lack of change in attentional demands of postural control with our fatigue protocols. First, fatiguing the hip or ankle muscles using concentric contractions may not have caused enough deficits in proprioception and postural control to increase the attentional demands of unipedal stance. Other than the relatively modest increase (less than 15%) in sway velocity, sway area and sway variability did not change immediately after fatigue. In comparison, the increase in attentional demands to maintain a static bipedal stance found in Vuillerme et al. [20] study was accompanied by an increase in postural sway range and greater increase in sway velocity (65% increase) due to an isometric fatigue protocol. Second, the fact that our subjects could rely on visual information may have attenuated the increase in attentional demands due to fatigue and could explain the lack of significance in this study. Nonetheless, further research is needed to thoroughly document the attentional cost of fatigue on postural control.

5. Conclusion

Fatigue in proximal (hip) muscles decreased postural control of a unipedal stance to a greater extent compared with fatigue of distal (ankle) muscles, possibly because the former muscles are more important in this specific task. The increase in attentional demands observed during the dual-task was not greater when subjects' ankle or hip muscles were fatigued. This suggests the presence of sufficient attentional resources to perform both tasks simultaneously after an isokinetic fatigue protocol.

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Conflict of interest

None of the authors have ties to any activities or industry that could inappropriately influence his or her judgment regarding this research or the results presented in the manuscript.

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